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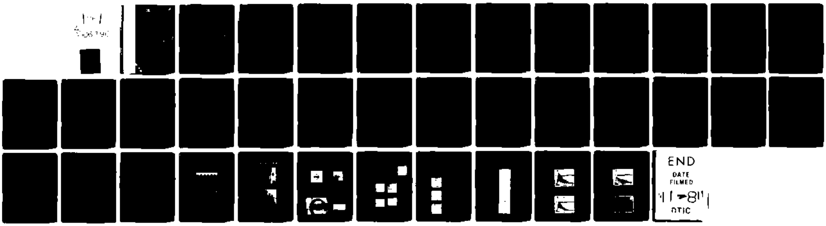

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W. M. Bollen

R. K. Parker, Naval Research Laboratory
W. M. Black, Naval Research Laboratory

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ABSTRACT

The physics of gas breakdown for large collision frequency, $\nu/\omega > 1$, is being pursued at the Naval Research Laboratory. The hybrid inverted coaxial magnetron, 500MW, 3.2 Ghz, 30ns pulse width, allows investigation of gas breakdown in the high ν/ω regime. The 35 Ghz gyrotron, 150KW, 300pps, allows investigation in a moderate ν/ω regime. Large gas breakdown plasma densities have been measured, $n \approx 100 n_c$. Spectral measurements have been made showing only excitation of molecular bands. Preliminary propagation experiments have also been performed.

CONTENTS

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1. INTRODUCTION

The study of microwave breakdown of air is not a new one. In the past many individuals have pursued research on the threshold for microwave breakdown of gases. An excellent review of this work is given by MacDonald.[1] These efforts were limited to threshold studies due to the power of the microwave sources available. Sufficient electric field strength to produce atmospheric breakdown levels were generated using high Q cavities. The ability to study the interaction between the breakdown plasma and the microwaves did not exist, since once the plasma formed, the Q of the cavity was greatly decreased.

With the advent of new high-power microwave sources [2,3,4] interest in air breakdown and the resulting microwave plasma interaction has gained new impetus.[5] In particular, the Naval Research Laboratory (NRL) has developed a Hybrid Inverted Coaxial Magnetron (HICM) with a peak power of 0.9 GW at a frequency of 3.2 Ghz (S-Band).[6] This source has been used to begin an experimental program at NRL to investigate the physics of microwave interaction with air.[7] This facility is unique in that energy deposition in the breakdown plasma can be investigated. The peak electric field, $E > 5\times10^4$ V/cm, is generated independent of a resonant cavity, and therefore deposition occurs for many microwave cycles ($\tau \sim 500/\omega$). It is the initial results of this experimental program that this report deals with.

First a short discussion of electromagnetic radiation interaction with air is given in Section 2. Then in Section 3, the experimental apparatus is discussed. The program has expanded and now includes more microwave sources than the original magnetron. Section 4 discusses the experimental results and their interpretation.

The goal of this program is to understand microwave interaction with gases in the regime where the collision frequency is larger than the plasma frequency, i.e., where $\nu/\omega_{pe} > 1$. To this end, the plasma density, temperature, emission and distribution function should be measured versus both time and space. As will be described, a first attempt at measuring some of these parameters has begun and is continuing.

2. THEORY

In the regime of interest to us, near 760 Torr pressure, microwave interaction with gases is a collisional process. The electron collision frequency, $\nu \approx 5.3 \times 10^9$ p (p = pressure in Torr), is large compared to our driver frequency, i.e., $\nu/\omega > 1$. Thus, strong classical coupling (due to inelastic collision of the electrons with the gas molecules) of the microwave power to the breakdown plasma is expected. Before this coupling can begin the gas must of course breakdown, that is, ionize.

When microwave energy larger than the breakdown threshold impinges on a gas, the electric fields of the microwaves accelerate any "free" electrons (from cosmic radiation for example). These electrons then collide with gas molecules and if they have sufficient energy (greater than the ionization potential for the gas), they knock-out additional electrons. The process then proceeds by avalanche. It should, therefore, be clear that breakdown depends on the electric field (power), time, pressure, and type of gas present.

The overall shape of the breakdown threshold is shown in Figure 2-1 and is taken from Felsenthal.[8] At low pressures the threshold increases because of diffusion and also because there are few molecules to collide with and, therefore, few to create the secondary electrons needed for avalanche. At high pressures the electron collides so often that it is difficult to gain the required ionization energy. Thus, the resulting parabolic shape (Pachen curve). The regime we are interested in is to the right of the Pachen minimum and for frequencies less than 100 Ghz, i.e., where $\nu/\omega > 1$.

We have talked about breakdown, but have not clearly defined it. For a non-pulsed system the definition is fairly straight forward. When the electron production is exactly balanced by the loss of electrons, the gas is considered to have broken down. Ionization is the gain term,

and there are three competing loss terms: (1) attachment, (2) diffusion and, (3) recombination. Diffusion dominates at low pressures, and at high pressures attachment dominates. From an experimental point of view, this balance is somewhat hard to measure. Further, in a pulsed experiment, this type of steady state may never be reached. In the high Q cavity experiments the point at which the cavity Q dropped and, therefore, the microwaves were strongly interacting with the plasma, was taken to be the point of breakdown. For a collisionless plasma this occurs when $\omega \approx \omega_{pe}$. This is also the definition of breakdown we will use in the collisional case ($\omega_{pe}^2 = 4\pi ne^2/m_e$). Thus, in attachment dominated experiments, breakdown occurs when $10^{13}/\lambda^2 = n_0 \exp(\nu\tau)$, where $\nu = \nu_i - \nu_a$, ν_i is the ionization frequency, ν_a is the attachment frequency, λ is the wavelength of the incident radiation, and n_0 is the initial electron density ($\sim 1 cm^{-3}$).

In order to understand how the microwaves behave when interacting with a collisional plasma, an expression for the rf electric field inside a collisional plasma can be derived. By using the two fluid equations, and assuming no steady state fields, and a cold plasma, and linearizing, it can be shown that the dispersion relation for a collisional plasma is:[7,8]

$$k^2 = \frac{\omega^2}{c^2} \left[1 - \frac{\omega_{pe}^2}{\nu^2 + \omega^2} \left(1 - \frac{i\nu}{\omega}\right)\right] . \qquad (2\text{-}1)$$

If we define: $\mu \equiv \mathrm{Re}\,(k)$

$\chi \equiv -\mathrm{Im}\,(k)$

$\alpha = \chi\, \omega/c$

$\beta = \mu\, \omega/c$

$\zeta = \alpha + i\beta$,

then the propagation of an electromagnetic wave in our uniform medium is $E \propto \exp\,(i\omega t - \zeta z)$, and α above is the attenuation constant. Assuming that $\nu \gg \omega$, we may write equation (2-1) as:

$$k_r = 1 - \frac{\omega_{pe}^2}{\nu^2} \qquad (2\text{-}2a)$$

and $$k_i = - \frac{\omega_{pe}^2}{\nu\omega} , \qquad (2\text{-}2b)$$

then, using the approximation in the appendix of Heald and Wharton[11], we can show that for $k_r^2 >> k_i^2$ and $k_i > 0$ (our case):

$$\mu \equiv k_r^{1/2} \left(1 + k_i^2/(8k_r^2)\right) \qquad (2\text{-}3a)$$

and $$\chi \equiv k_r^{1/2} \left(k_i/(2k_r)\right) \quad . \qquad (2\text{-}3b)$$

Thus, we can calculate α, and determine the absorption. The physical meaning of α is related to the skin depth, $\delta = 1/\alpha$, and is expressed in units of centimeters. Thus, $\delta = (c/\omega)2k_r^{1/2}/k_i$, and increases approximately linearly with the collision frequency.

The detailed derivations for electromagnetic interaction with plasma slabs and the inclusion of magnetic fields has been done by Heald and Wharton[11].

We now have an understanding of how the microwaves will interact with a highly collisional plasma. We expect the large number of collisions to increase the skin depth and allow penetration of the plasma for densities much larger than the collisionless critical density. We also expect the large number of inelastic collisions of the electrons with the neutral gas, which become internal energy and eventually result in heating, to efficiently couple the energy from the microwaves to the gas.

3. EXPERIMENTAL SET-UP

The air breakdown research at NRL uses the NRL high-power inverted coaxial magnetron. This is an S-Band, 3.2 Ghz, 30 ns, 0.8 GW source (see Figure 3-1) with microwaves output in the TE_{01} mode (see Figure 3-2) into a 20 cm oversize waveguide. The TE_{01} is a low loss propagation mode. Plans call for the pulse length to be increased on this source.

Recently we have also begun research using a lower power, higher frequency source, the 35 Ghz NRL gyrotron. This 150 KW source supplies 35 Ghz, 1μs pulses at up to 300pps.

The high repetition rate is useful in some applications, and information on frequency scaling can also be obtained by using the second frequency. Unfortunately, at present, the power is far too low to perform breakdown research near one atmosphere, and studies must be done at 50 Torr. At this pressure $\nu/\omega \sim 1$, and we are in a transitional, rather than collision dominated, regime.

We will first describe the air breakdown experiment using the magnetron as a source, and then quickly describe the gyrotron experiment. Figure 3-3 shows a schematic of the existing magnetron system. The microwave power is monitored using a specially designed bi-directional coupler. The air breakdown chamber is shown. It is a section of the waveguide with a Mylar window on one end. This acts as a vacuum seal allowing the magnetron to be at low pressure ($p<10^{-5}$ Torr) and the breakdown cell to be at atmospheric pressure. The cell also has two windows for viewing the breakdown region. These windows are designed so that the cuts in the waveguide wall have only a small effect on the microwaves. An alternative section with no windows, but with probe ports, can be added to allow use of Langmuir probes. All the 3.2 Ghz data described in this report was taken using the magnetron source and this cell.

A new diagnostic chamber allowing for better access has been designed and is being phased into the system (see Figure 3-4). This chamber differs from the cell in that it is a quasi-focused system, as shown in Figure 3-5. A focused system better simulates a free air breakdown far from surfaces.

The gyrotron experiment (see Figure 3-6) is a focused system. A horn expands the microwaves, which are then focused using a dielectric lense. The chamber is a plexiglass box with access points for probes, gas inlet, etc. The focal spot for this system is less than 2λ in diameter. The total 3db focal spot is approximately 2 cm^2.

The plasma density diagnostics used to date in both experiments have been Langmuir probes. These were constructed using four mil tungsten wire. We have used the collisional theory of Kiel[12] to analyze data obtained using these probes. Using Kiel's theory, we obtain,

$$I_j = \frac{n\ 2\pi L}{\ln(\pi L/4r_p R_s)} \ \frac{ekT_e}{m_j\ \nu_{jn}} \text{ amps,} \qquad (3\text{-}1)$$

where:

n = plasma density

I_j = current collected

L = probe length

r_p = probe radius

k = boltzman constant

e = charge constant

m_j = mass of species j

ν_{jn} = collision frequency species j with neutrals

T_e = electron temperature

$R_s = 1 + a\left(\lambda_D/r_p\ \ \phi(\text{volts})/T_e(\text{ev})\right)^{0.62}$ (a=2.5 for our case)

$\nu_{en} = 5.3\times10^{9}\ p(\mathrm{Torr})$

$\nu_{in} = 1.4\times10^{6}\ p(\mathrm{Torr})$

λ_D = Debye Length

This equation was used in analyzing all of our Langmuir probe data.

4. EXPERIMENTAL DATA

The experimental data obtained using both the magnetron and the gyrotron will be discussed and compared. Recall that the important parameter ν/ω is different for the two cases, due to the difference in operating frequency and pressure.

4.1 MAGNETRON AIR BREAKDOWN RESEARCH

Work has begun using the HICM to investigate the physics of air breakdown. Mode impurity problems have plagued the early stage of the program, but we have been able to begin measurements of the plasma density in the breakdown plasma. Theoretically, breakdown in air at atmospheric pressure is expected to occur at approximately 1.5 MW/cm^2 of microwave energy. For our experimental configuration with a TE_{01} mode, breakdown would occur first at a ring with about a 5 cm radius at 250 MW of microwave power. The TE_{01} mode has approximately a factor of two enhancement in power, at the 5 cm radius, over an evenly distributed pattern of power. Due to the mode impurity problems, the complete factor of two enhancement will not occur. We are correcting our mode problems; and expect, in the near future, to be operating in a pure TE_{01} mode.

The mode impurity problem required reassessment of window design in order to eliminate initial window arcing. Figure 4-1 shows this arcing. It was eliminated by using cross strips on the window slots. This can be seen in Figure 4-2. Photography of the breakdown looking sideways and down the guide (Figure 4-2) shows a great deal of structure. The structure seen in the end-on view is not the expected ring structure for the TE_{01} mode, and must be due to the effect of other modes being present. We do not, at this time, understand the structure seen in the sideview.

Experiments to measure the plasma density using Langmuir probes were also performed. This diagnostic technique suffers from two problems: (1) unreliability until after turn-off of microwaves and, (2) possible inducement of breakdown. For the time being, it does offer a reasonable estimate of the plasma density after the microwave pulse. (A microwave interferometer is being constructed for future use.) Figure 4-3 shows data taken for two different pressures. An aluminum short was utilized to insure breakdown at atmospheric pressure. The probe was not placed at $\lambda/4$ from the plate, but rather many wavelengths in front. It was expected that the volume would fill with plasma, based on the photographs of breakdown. The probe was placed at the radius for maximum electric field. As can be seen in the figure, there is a large amount of shot-to-shot variation. For both pressure ranges, the density is $n_e > 10^{14} cm^{-3}$. This is an extremely large density if $\nu < \omega$, since the critical collisionless density ($\omega_p = \omega$) is $n_{co} = 1.3 \times 10^{11}$ cm^{-3}. However, if collisional effects are included, the critical density ($\omega_p = \nu$) is found to be $n_{cc} \approx 5 \times 10^{15}$ (760 Torr). Critical density is the point at which the dielectric constant becomes completely imaginary, so that the wave becomes evanescent at that point.

Plasma densities of this order were observed using both electron and ion current measurements. Further, computations by C. Yee[13] using the NRL (CHMAIR) code[14] predict the decay constant for a $10^{14} cm^{-3}$ plasma at 100 Torr pressure to be 140 ns. This is in extremely good agreement with our 160 ns measurement. The NRL (CHMAIR) code includes diffusion and air chemistry.

Good correlation between maximum plasma density and microwave power has not yet been achieved. With the resolution of the mode impurity problem, we expect to accomplish this shortly. Improvement in density measurements using microwave interferometry is also expected.

Preliminary measurements of propagation have also been made, as can be seen in Figure 4-4. Trace #2 is transmitted power and trace #1 is forward power. The forward power will have reflected power superimposed upon it with a time delay. This is due to reflection off the magnetron's output coupling disc. This reflected pulse is seen in the lower two traces, and occurs very near the 50ns delay one would calculate using the geometry of the experimental system. Photo #1 shows no breakdown. At 350 millitorr breakdown occurs. We see that trace #2 is shortened, suggesting total reflection of the incoming wave part way into the pulse. For 350 millitorr, $\nu/\omega \approx 0.1$, we are "collisionless". Also seen in trace #1 is the reflected pulse.

At 10 Torr, $\nu/\omega \approx 2.5$, we are also near the minimum of the breakdown threshold. In this case, the pulse is seen to be entirely reflected. In fact, the front edge of the pulse, pre-breakdown, must have been transmitted, since prior to plasma formation, there can be no reflection. The formation of the plasma must have been so fast that this transient pulse was undetectable by our system. At this time higher pressure studies are underway.

4.2 GYROTRON AIR BREAKDOWN RESEARCH

We have also been using the NRL gyrotron to perform air breakdown experiments. As mentioned earlier, this is in a slightly different regime where $\nu/\omega \approx 1$. The high repetition rate of the gyrotron has allowed us to use a spectrometer to measure the spectra of the light output from air breakdown plasmas. Attempts to do this on the one shot magnetron system met with failure, due to the small amount of light output on one shot and high loss of the spectrograph. (An attempt at mulitple shots (500 over a one hour period) was made but met with no success). We used a Spex 3/4 meter Everny-Turner monochrometer/spectrograph. The data taken on the gyrotron is shown in Figure 4-5. Mercury lines were used for

calibration. This system had $\Delta\lambda$=0.5Å. It is clear from the data shown that it is the molecular bands that are being excited. The system was scanned from 3000-5000Å, and no atomic lines were seen.

We also measured the plasma density using a Langmuir probe. Measurements at 5 Torr ($\nu/\omega\approx.12$), Figure 4-6, gives a plasma density of about $1\times10^{11}cm^{-3}$ for power of ≈60 KW/cm^2. At 50 Torr ($\nu/\omega\approx1.2$), the system was very noisy (see Figure 4-7). The plasma density was approximately $1\times10^{13}cm^{-3}$ again for power of ≈60 KW/cm^2 at 35 Ghz; $n_c(\omega=\omega_p)$ is 1.5×10^{13}. It is clear that, as the collision frequency increases, so does the plasma density. Thus, the large density values observed with the magnetron ($\nu/\omega\approx28$) seem very reasonable.

This work is preliminary and much still remains to be done. In particular, a measurement of the electron temperature is very important. Work is underway to do this using the nitrogen line spectra. As mentioned earlier, an interferometer system is under construction to aid in the density measurements.

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FIGURE CAPTIONS

Figure 2-1 - Shown are pulse microwave air breakdown thresholds versus pressure for different pulse lengths and microwave frequency. This is taken from Felsenthal[8].

Figure 3-1 - The NRL Hybrid Inverted Coaxial Magnetron is shown in cross section.

Figure 3-2 - The TE_{01} mode is sketched in three perspectives. This is the mode used in the 3.2 Ghz experiments.

Figure 3-3 - Schematic representation of the 3.2 Ghz air breakdown experiments. This system is modular so that more sections, such as additional directional couplers, may be added.

Figure 3-4 - Focused microwave air breakdown chamber for 3.2 Ghz.

Figure 3-5 - Plot of microwave energy vs distance for device shown in Figure 3-4.

Figure 3-6 - Schematic of air breakdown chamber for 35 Ghz experiments.

Figure 4-1 - Window sparking probably resulting from mode impurities.

Figure 4-2 - Photographs of air breakdown using set-up shown in Figure 3-3. Upper photo was taken perpendicular to direction of propagation. Lower photo was taken looking down wave guide by replacing load section with a window. Microwave power as monitored by a crystal detector is shown to the right of each photo. Time scale for both is 100ns/div.

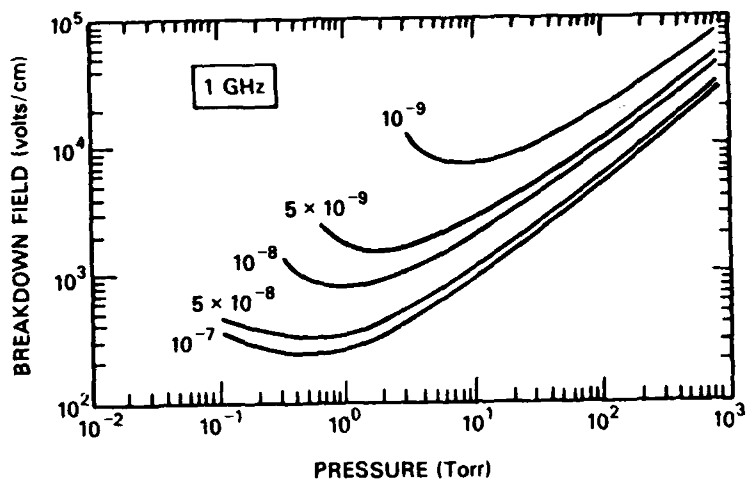
Figure 4-3 - Breakdown at different pressures, as measured using a Langmuir probe. The breakdown was in front of a reflecting metallic surface.

Figure 4-4 - Effects of microwave propagation through breakdown discharge are shown. Traces are for crystals located as shown in diagram. The second peak in trace 1 in the bottom two cases is due to reflection. The microwaves reflect off of the breakdown plasma, and again off of the coupling disk, resulting in a delayed signal in the forward direction. The delay is correct for the lengths involved.

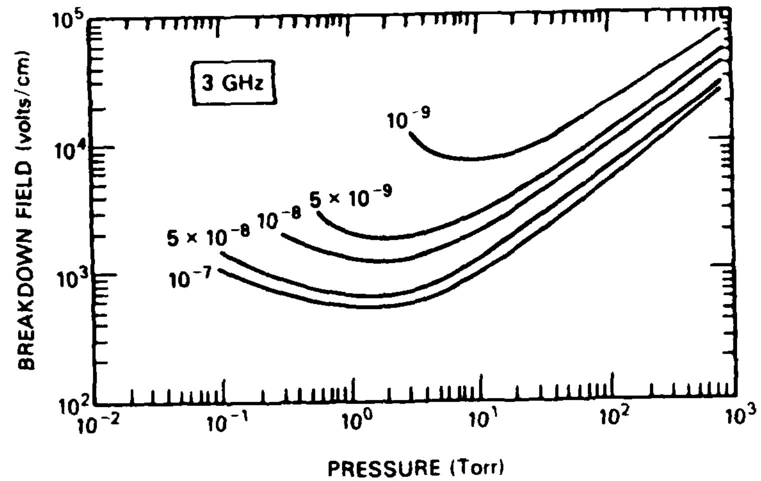
Figure 4-5 - Optical spectrum observed using 35 Ghz 114KW focused microwaves at 50 Torr of air pressure.

Figure 4-6 - Electron and ion densities measured at a 5 Torr air pressure using a Langmuir probe in the 35 Ghz experiment. The upper trace is the microwave pulse as monitored using a crystal. The lower trace is the probe. The time scale is 2µs/div. The electrons are 2V/div and the ions 0.2 V/div.

Figure 4-7 - This is the same as 4-6 but at an air pressure of 50 Torr. Time scale is 2µs/div. The electrons are 1v/div and the ions 0.5v/div.



PRESSURE-vs-BREAKDOWN-VOLTAGE CURVES FOR 1 GHz FOR VARIOUS PULSE LENGTHS



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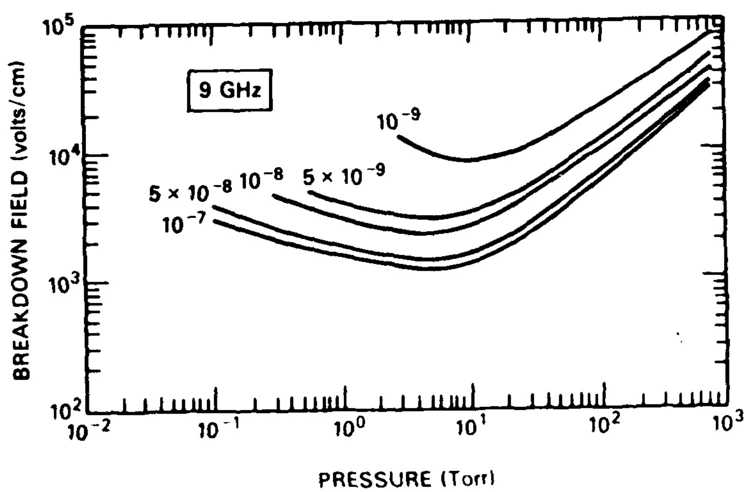
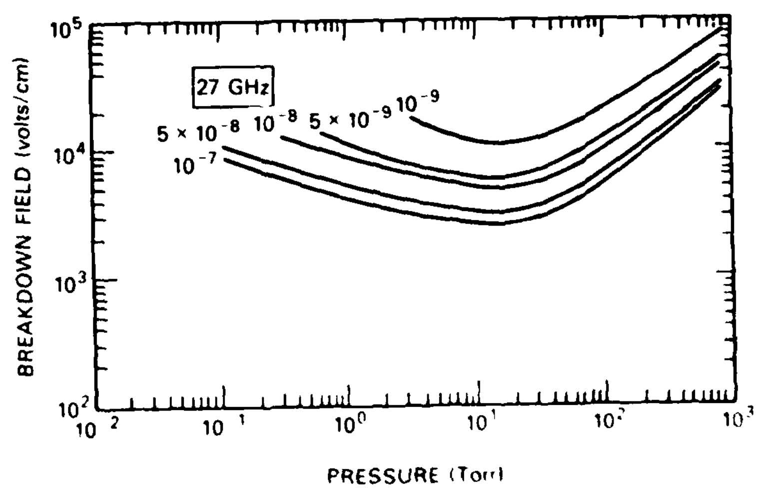


PRESSURE-vs-BREAKDOWN-VOLTAGE CURVES FOR 9 GHz FOR VARIOUS PULSE LENGTHS



PRESSURE vs BREAKDOWN VOLTAGE CURVES FOR 27 GHz FOR VARIOUS PULSE LENGTHS

Figure 2-1

(From Felsenthal)

Figure 3-1

TE_{01} CIRCULAR MODE

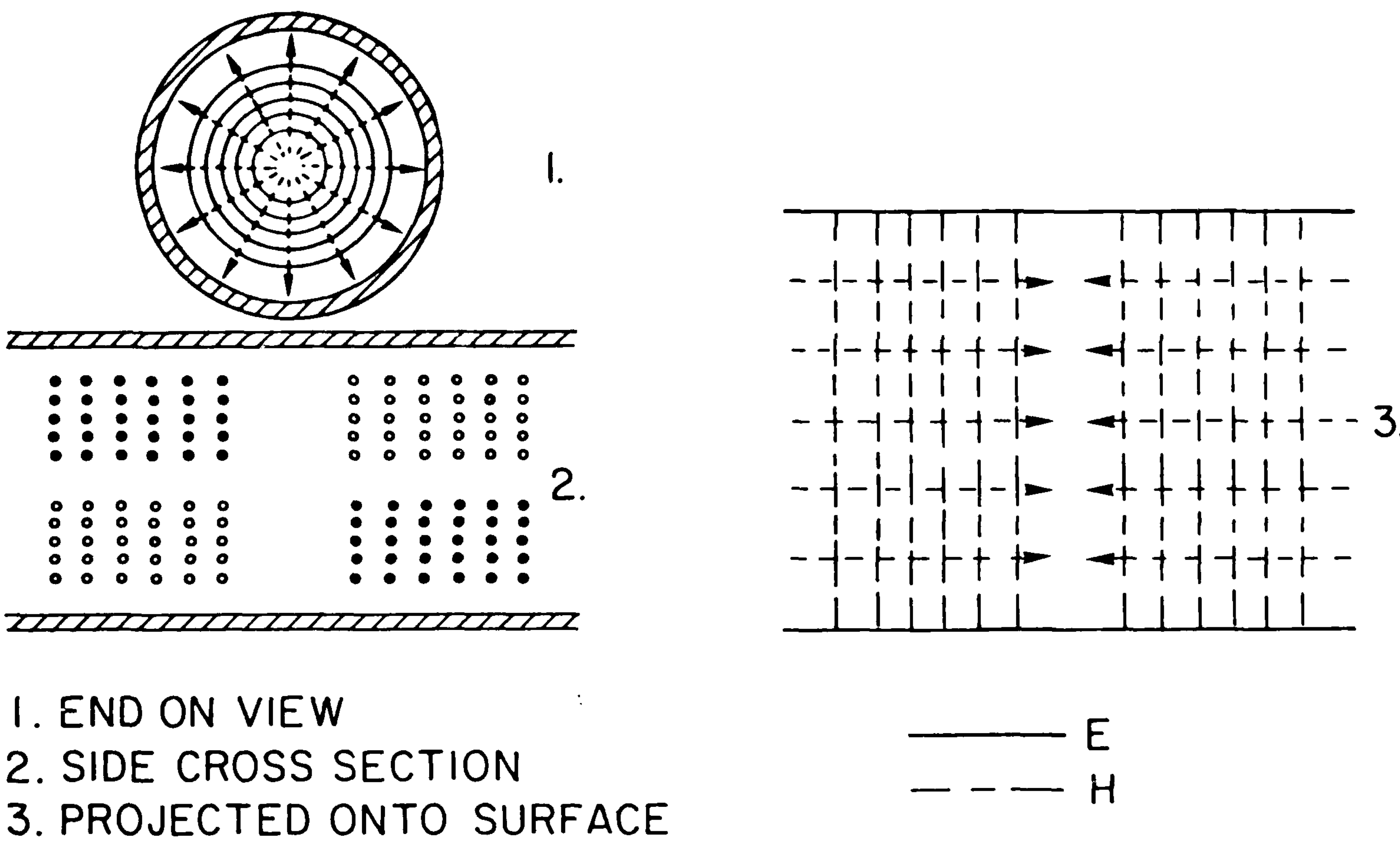


Figure 3-2

SCHEMATIC OF AIR BREAKDOWN DEVICE USING MAGNETRON

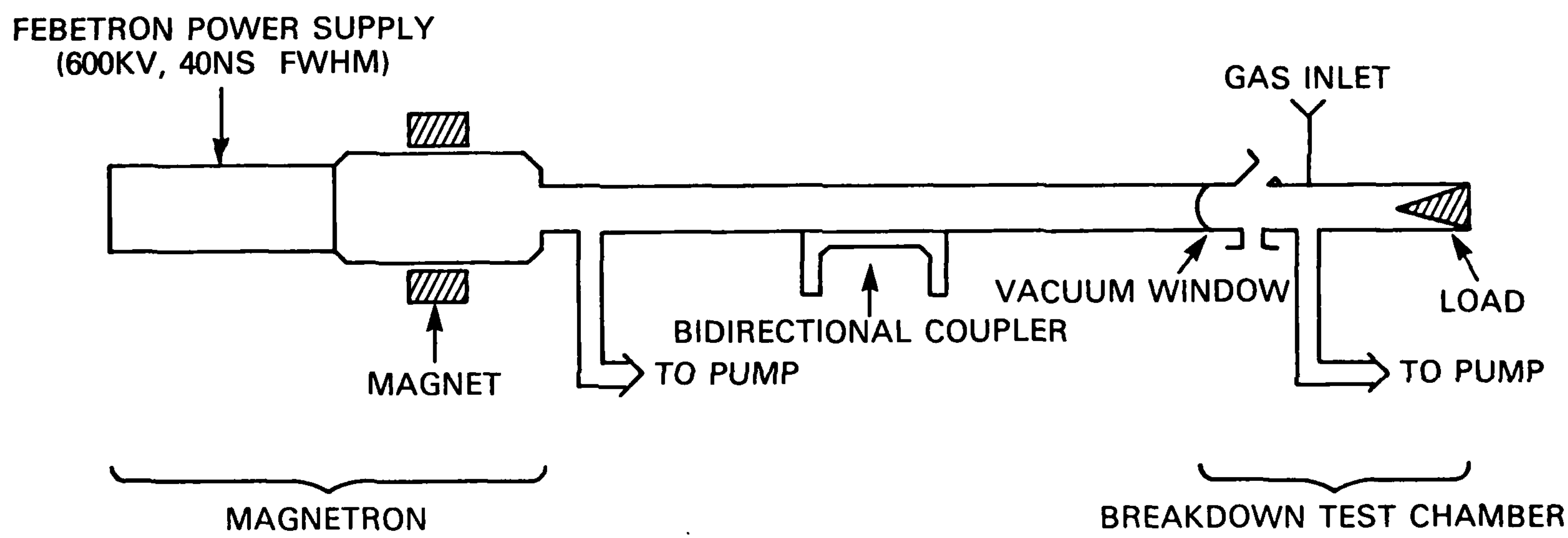
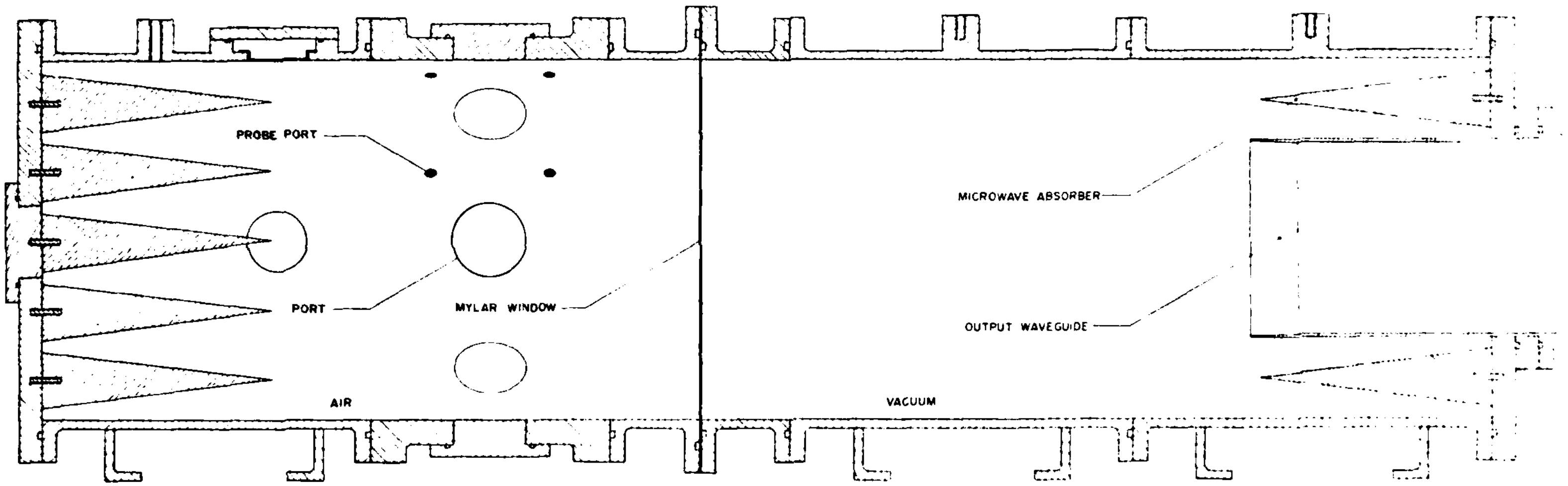


Figure 3-3



TARGET CHAMBER

Figure 3-4

FOCUSED MICROWAVE ENERGY PATTERN

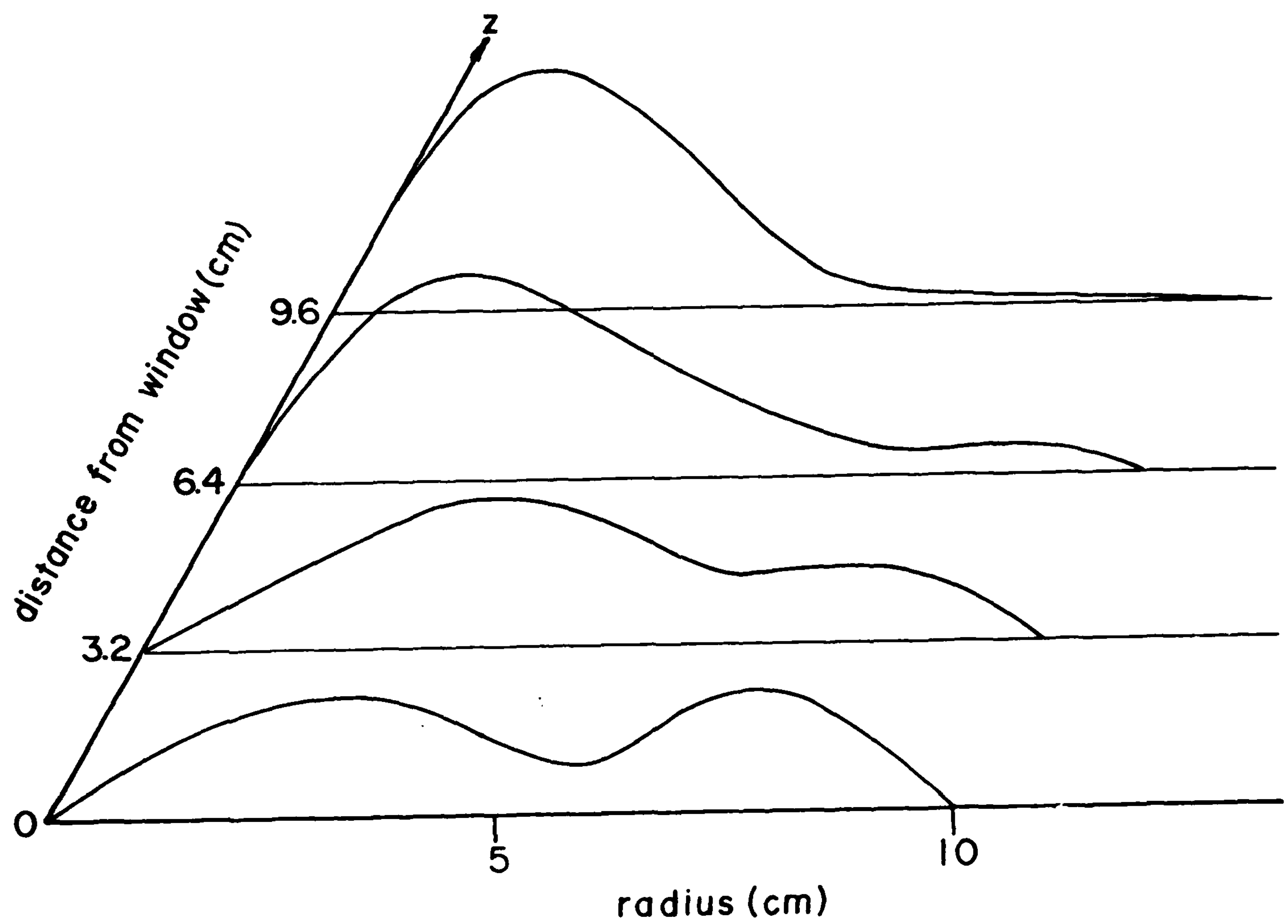


Figure 3-5

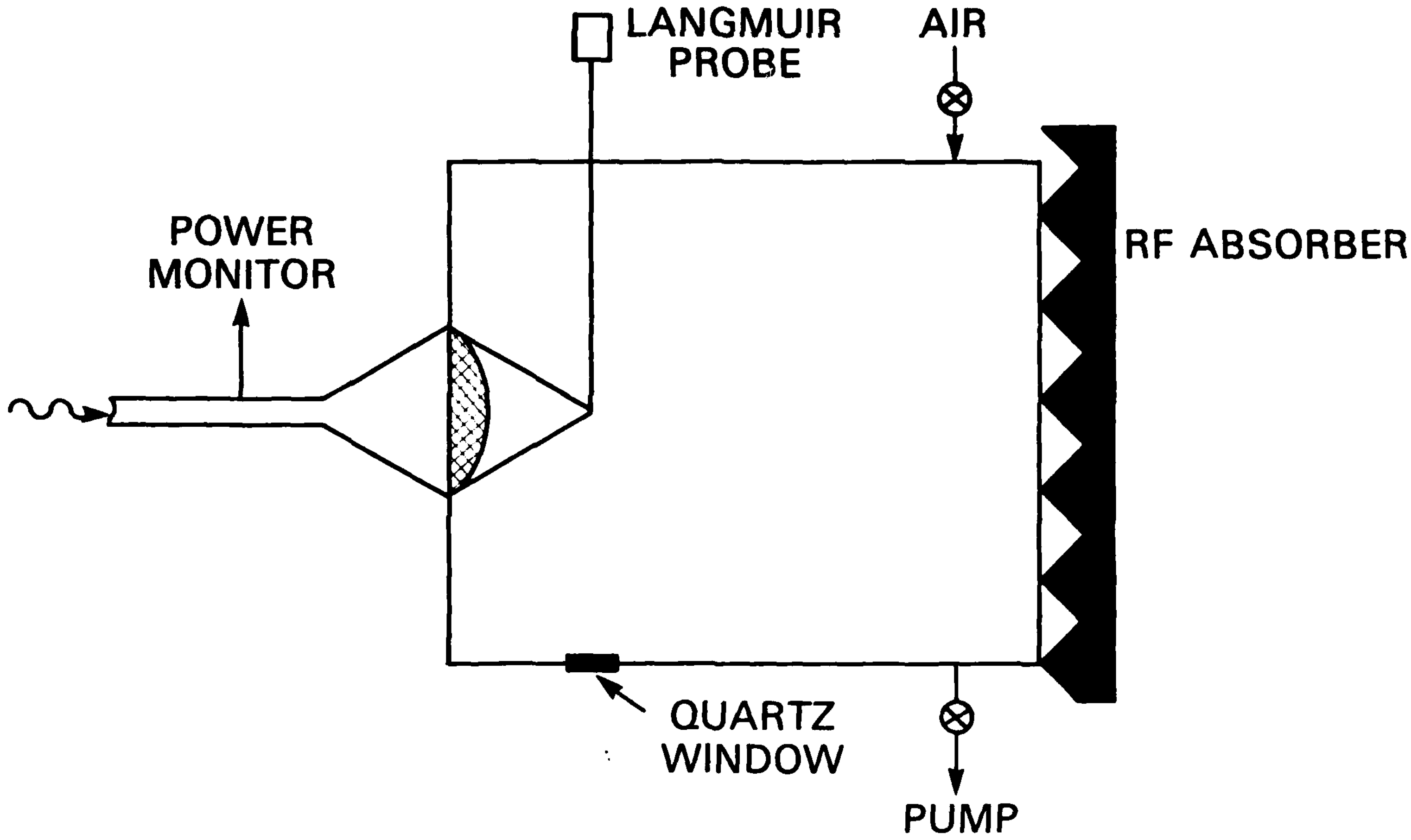

LANGMUIR
PROBE
AIR
POWER
MONITOR
RF ABSORBER
QUARTZ
WINDOW
PUMP

Figure 3-6

WINDOW SPARKING

NO MICROWAVES

300 MW PEAK MICROWAVE POWER

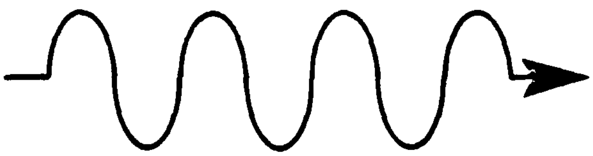


Figure 4-1

PHOTOGRAPHS OF AIR BREAKDOWN

AIR BREAKDOWN AT 10 TORR AS SEEN THROUGH SIDE WINDOW (3 SHOTS)

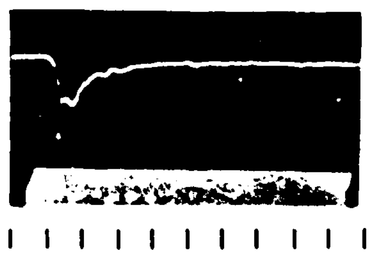
MICROWAVES

<P> =400 MW

AIR BREAKDOWN
VIEWED WITH OPEN SHUTTER
CAMERA (1 SHOT)

PRESSURE = 70 TORR

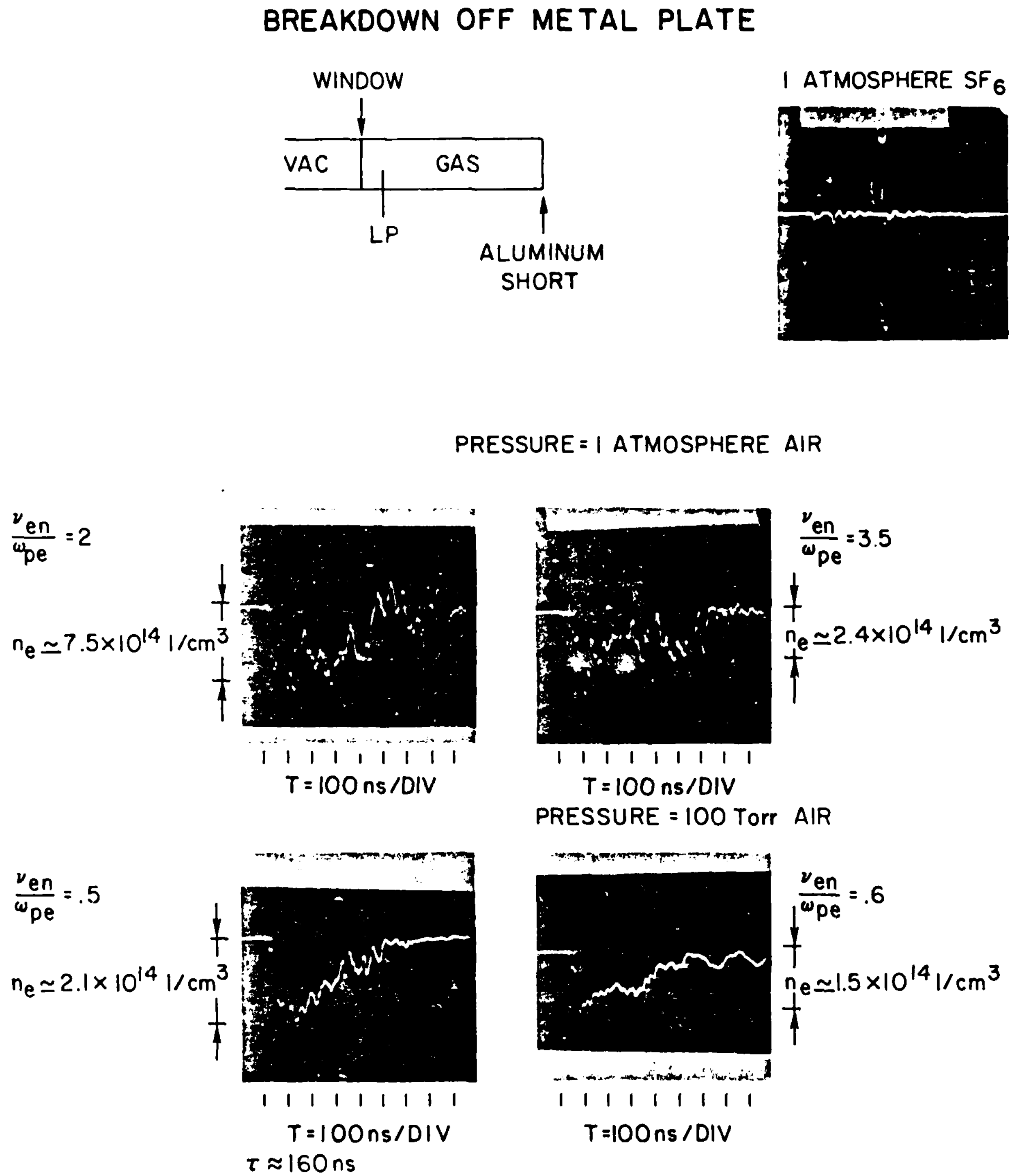
MICROWAVE POWER



100 ns/DIV

P = 60 MW

Figure 4-2



BREAKDOWN OFF METAL PLATE
WINDOW
VAC
GAS
LP
ALUMINUM SHORT
1 ATMOSPHERE SF_6
PRESSURE = 1 ATMOSPHERE AIR
$\frac{\nu_{en}}{\omega_{pe}} = 2$
$n_e \simeq 7.5 \times 10^{14}$ 1/cm^3
T = 100 ns/DIV
$\frac{\nu_{en}}{\omega_{pe}} = 3.5$
$n_e \simeq 2.4 \times 10^{14}$ 1/cm^3
T = 100 ns/DIV
PRESSURE = 100 Torr AIR
$\frac{\nu_{en}}{\omega_{pe}} = .5$
$n_e \simeq 2.1 \times 10^{14}$ 1/cm^3
T = 100 ns/DIV
$\tau \approx 160$ ns
$\frac{\nu_{en}}{\omega_{pe}} = .6$
$n_e \simeq 1.5 \times 10^{14}$ 1/cm^3
T = 100 ns/DIV

Figure 4-3

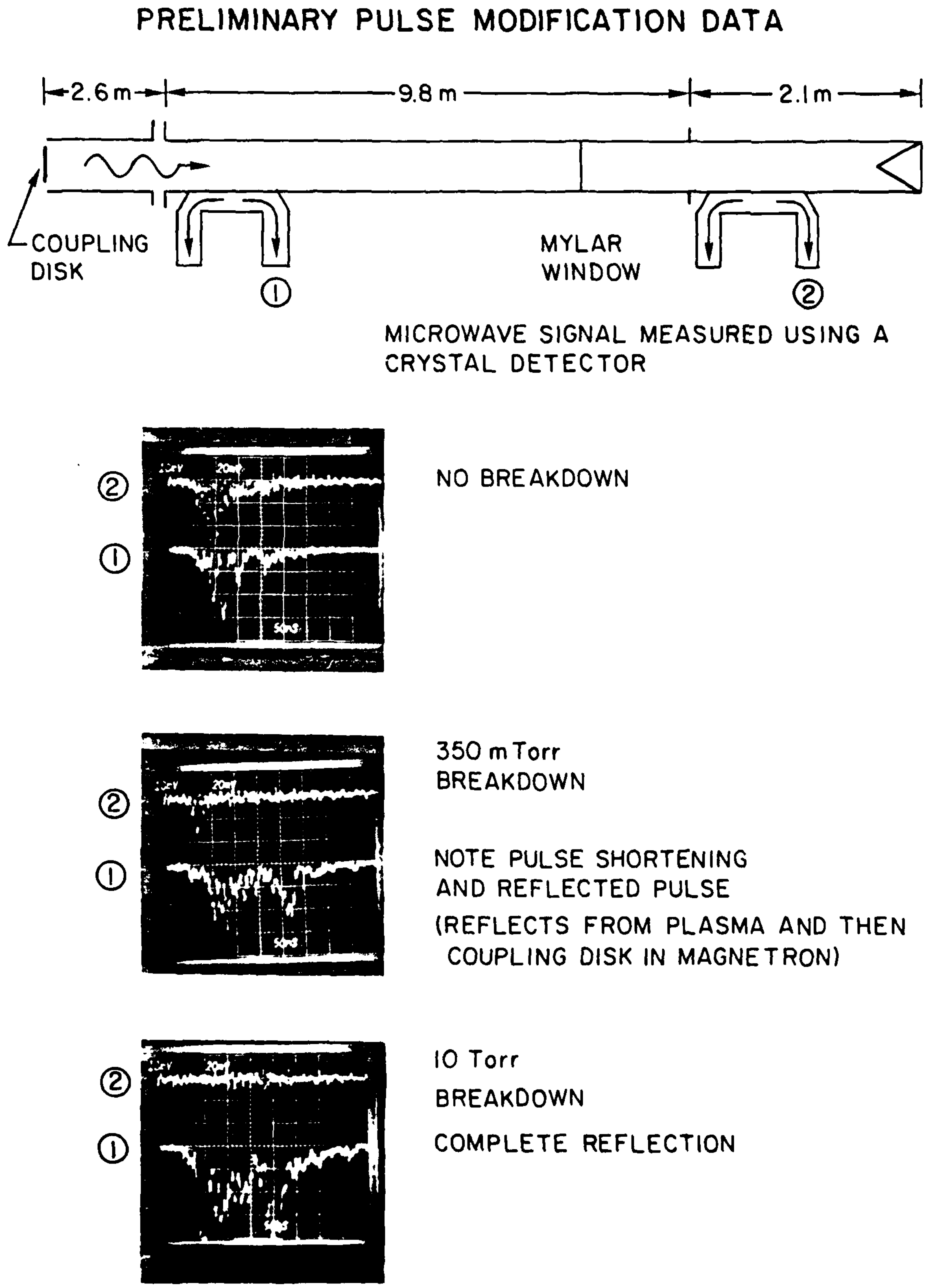

PRELIMINARY PULSE MODIFICATION DATA
2.6 m
9.8 m
2.1 m
COUPLING DISK
MYLAR WINDOW
①
②
MICROWAVE SIGNAL MEASURED USING A CRYSTAL DETECTOR
②
①
NO BREAKDOWN
②
①
350 m Torr
BREAKDOWN
NOTE PULSE SHORTENING AND REFLECTED PULSE
(REFLECTS FROM PLASMA AND THEN COUPLING DISK IN MAGNETRON)
②
①
10 Torr
BREAKDOWN
COMPLETE REFLECTION

Figure 4-4

AIR SPECTRUM
GYROTRON POWER = 114 kW
PRESSURE = 50 TORR

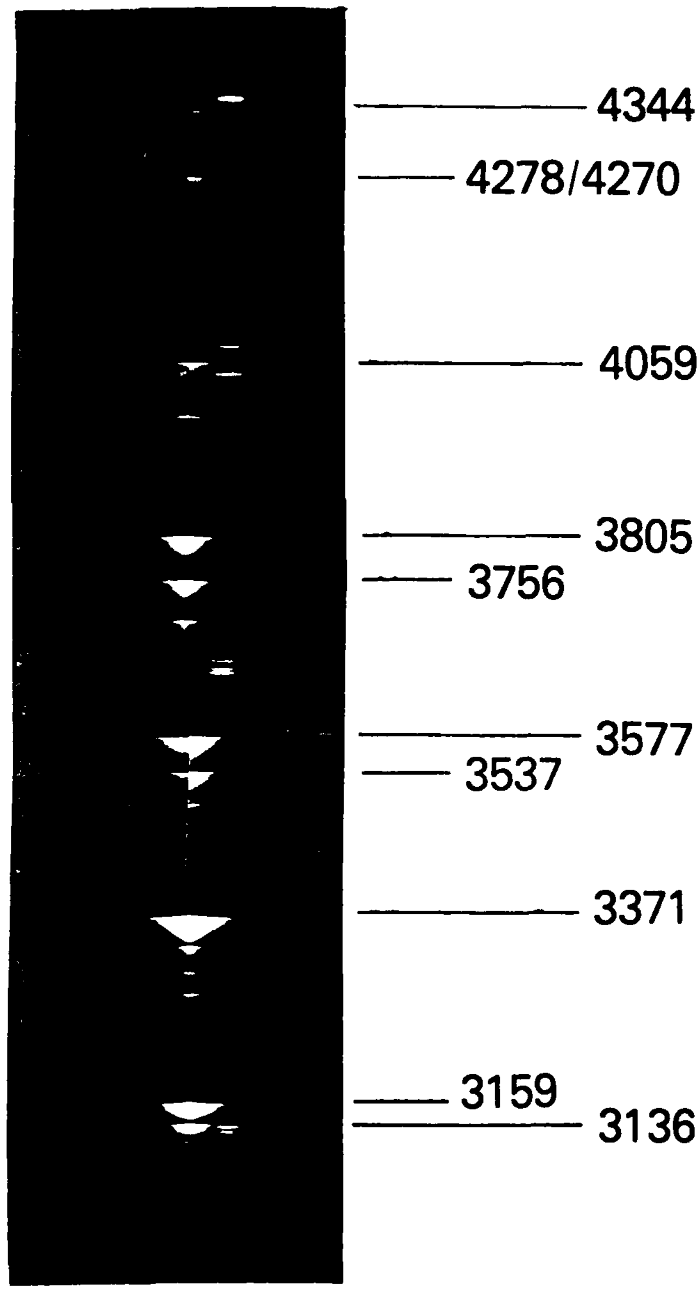
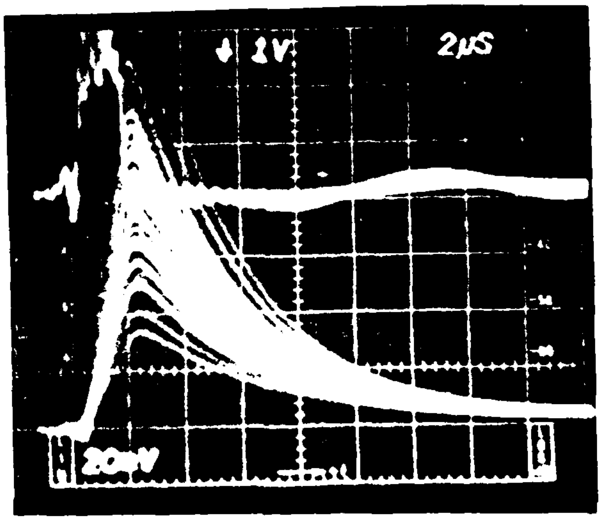


Figure 4-5

PROBE MEASUREMENTS USING BOTTLED AIR
PRESSURE = 50 TORR   POWER = 110 KW

ELECTRONS
$n_e = 6 \times 10^{12}\ cm^{-3}$



IONS
$n_e = 2.9 \times 10^{13}$

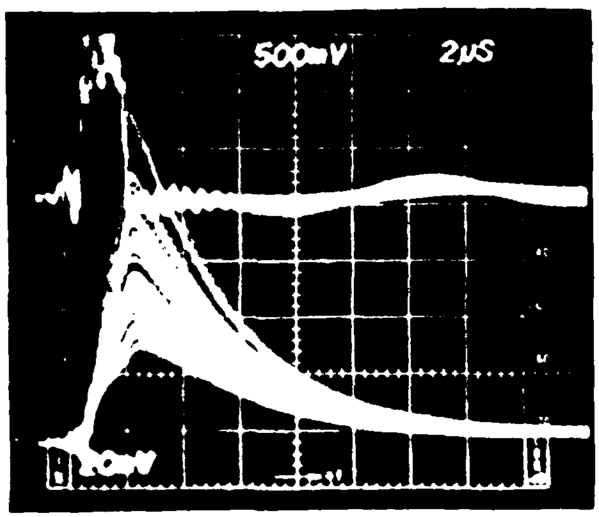
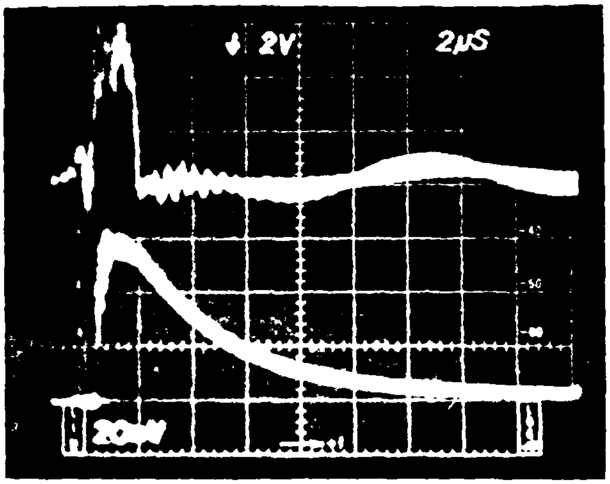


Figure 4-6

PROBE MEASUREMENTS USING BOTTLED AIR
PRESSURE = 5 TORR   POWER = 110 KW

ELECTRONS
$n_e = 9.9 \times 10^{10}$ cm^{-3}



IONS
$n_e = 1.06 \times 10^{11}$ cm^{-3}

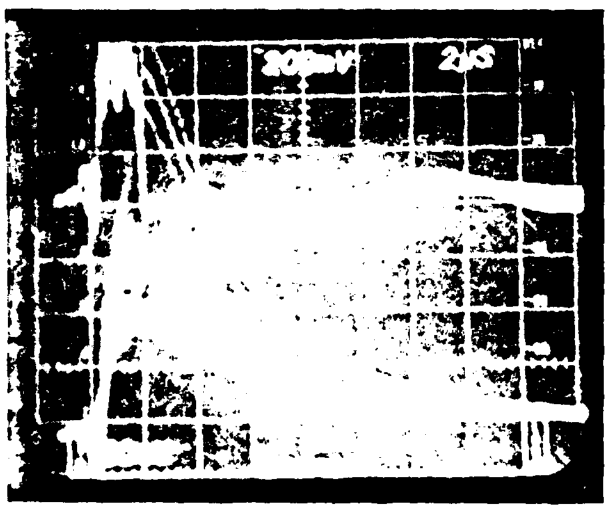


Figure 4-7


FILME